AD A

LOWERING USAF DIESEL ENGINE NOx EMISSIONS WHILE UTILIZING B20 BIODIESEL FUEL

INTERIM REPORT
TFLRF No. 380

by

Douglas M. Yost

U.S. Army TARDEC Fuels and Lubricants Research Facility
(SwRI®) Southwest Research Institute®
San Antonio, TX

Under Contract to
U.S. Army TARDEC
Petroleum and Water Business Area
Warren, MI

Contract No. DAAE-07-99-C-L053 (WD25)

Approved for public release: distribution unlimited

September 2005

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Edwin C. Owens, Director
U.S. Army TARDEC Fuels and Lubricants
Research Facility (SwRI)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY	2. REPORT DATE September 2005	3. REPORT TYPE AND DATES COVERED Interim, June 2003 – September 2005

4. TITLE AND SUBTITLE Lowering USAF Diesel Engine NOx Emissions while Utilizing B20 Biodiesel Fuel	5. FUNDING NUMBERS DAAE-07-99-C-L053 WD 25
6. AUTHOR(S) Yost, D.M.	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI) Southwest Research Institute P.O. Drawer 28510 San Antonio, Texas 78228-0510	8. PERFORMING ORGANIZATION REPORT NUMBER TFLRF No. 380
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army TACOM U.S. Army TARDEC Petroleum and Water Business Area Warren, MI 48397-5000	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The United States Air Force can utilize B20 biodiesel fuel to partially meet EPAct requirements for alternative fuel use, and to lower criteria pollutants except for NOx. Relatively minor production component changes, and selected minor operating condition changes can alter engine out NOx emissions with biodiesel fuels in a 6.5L HMMWV engine. For a nonroad ISO 8178 test cycle, weighted average Smoke/PM emissions can be similar to DF-2 levels at the condition that gives equivalent NOx emissions with B20 biodiesel fuel. In other words, Smoke/PM emissions with B20 biodiesel can be traded-off for improved NOx emissions. For the 6.5L HMMWV engine tested the composite control strategy did not severely impact emissions or fuel consumption when the engine operated on JP-8 fuel.

14. SUBJECT TERMS NOx Biodiesel Emissions Fuel Diesel Engine	15. NUMBER OF PAGES 30
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

EXECUTIVE SUMMARY

The United States Air Force can utilize B20 biodiesel fuel to partially meet EPAct requirements for alternative fuel use, and to lower criteria pollutants except for NOx. However, based on B20 effects of lowering Particulate Matter (PM) emissions, and the knowledge of a PM for NOx tradeoff in diesel engines, procedures could be taken to lower NOx with B20 fuel by sacrificing the B20 PM benefit. The scope of this project was to look at simple, economical, and reversible approaches to lower NOx emissions when using B20 fuel at CONUS installations in a 6.5L HMMWV engine. The following conclusions are based on the data generated in this program for the 6.5L HMMWV engine.

- Relatively minor production component changes, and selected minor operating condition changes can alter engine out NOx emissions with biodiesel fuels in a 6.5L HMMWV engine.

- Over the nonroad test cycle weighted average NOx emissions can be similar to DF-2 emissions provided the control parameters of injection timing and EGR are adjusted based on engine load.

- For the nonroad test cycle weighted average Smoke/PM emissions can be similar to DF-2 levels at the condition that gives equivalent NOx emissions. In other words, Smoke/PM emissions with biodiesel can be traded-off for improved NOx emissions.

- For the 6.5L HMMWV engine tested the composite control strategy did not severely impact emissions or fuel consumption when the engine operated on JP-8 fuel.

FOREWARD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period June 2003 through September 2005 under Contract No. DAAE-07-99-C-L053. The author would like to acknowledge the efforts of Mr. William Likos at WR-ALC and Mr. Luis Villahermosa at U.S. Army TARDEC for technical guidance during the course of the project. The following staff at SwRI should be acknowledged for their contribution to this project, Mr. Matt Schulman, project test engineer, Mr. James Sczepanik and Mr. Steven Schneider for engine installation and operation, and Mr. Thomas Aguilar for emission bench operation. The author gratefully acknowledges Ms. Linda De Salme of SwRI for her clerical efforts during the course of the project.

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (continued)

SYMBOLS AND ABBREVIATIONS

A_E	Alamo Engine
ASTM	American Society for Testing and Materials
BSFC	Brake Specific Fuel Concentration
BSNOx	Brake Specific Oxides of Nitrogen
BTDC	Before Top Dead Center
C	Celsius
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
EPAct	Environmental Protection Act
HC	Hydrocarbons
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
kPa	Kilo-pascals
L	Liter
NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PM	Particulate Matter
rpm	Revolutions per Minute
S	Sulfur
SwRI	Southwest Research Institute
TARDEC	United States Army Tank-automotive RD & E Center
TFLRF	United States Army TARDEC Fuels and Lubricants Research Facility
USAF	United States Air Force
WR-ALC	Warner Robins - Air Logistics Center

1.0 OBJECTIVE

The United States Air Force operates diesel engine powered aircraft ground support equipment in several ozone non-attainment zones. Precursors to ozone formation are ambient Oxides of Nitrogen (NOx) and Hydrocarbons (HC) emissions from combustion. The Air Force can utilize B20 fuel to partially meet EPAct requirements for alternative fuel use, and to lower criteria pollutants except for NOx. However, based on B20 effects of lowering Particulate Matter (PM) emissions, and the knowledge of a PM for NOx tradeoff in diesel engines, procedures could be taken to lower NOx with B20 fuel by sacrificing the B20 PM benefit. The scope of this project was to look at simple, economical, and reversible approaches to lower NOx emissions when using B20 fuel at CONUS installations.

2.0 INTRODUCTION AND BACKGROUND

Biodiesel fuels have demonstrated exhaust emission benefits in compression ignition or diesel engines. The Environmental Protection Agency recognizes that 20 volume % biodiesel added to diesel fuel (B20) results in the following emission reductions: 10.1% in PM; 21.1% in HC; and 11.0% in Carbon Monoxide (CO). A concomitant NOx emissions increase of 2.0% has been recognized with B20 fuel, along with a 1-2% fuel economy penalty [1]. However, the data are aggregate averages over various engine types, sizes and calibrations, base fuels, and types of biodiesel (soybean, rapeseed, or animal fats).

3.0 APPROACH

The project approach included the following: formulation of a B20 fuel; selection of engines with WR-ALC input; and engine-specific NOx-formation modeling studies. The baseline engine and fuels emission performance was evaluated along with parametric sweeps (determined from modeling) for engine and B20 fuel emission sensitivity. The modified engine was evaluated using JP-8 to determine deployment impacts of modifications.

3.1 Fuel Formulation – The base fuel used for all formulations was be a fuel that meets the Environmental Protection Agency (EPA) grade 2-D low-sulfur (0.05% S max.) certification fuel requirements. The base fuel will be checked for conformity to the

ASTM D-975 grade 2-D requirements. An additional fuel was MIL-T-83133 grade JP-8.

The B20 fuel was blended using B100 from soybean (methyl soyate) biodiesel sources. All B100 biodiesel obtained for blending was specified to meet the ASTM D-6751 specification requirements.

3.2 Engines - Representative Air Force ground support equipment engines were selected for study. A likely engine candidate was from the USAF A/M32-86D (Dash 86) generator. The Detroit Diesel 4-71N is a 72-kW blower-scavenged, naturally aspirated, two-cycle, quiescent chamber, direct-injected diesel engine of vintage design and mechanical fuel injection control technology. Several USAF programs over the years have addressed NOx reductions with this engine. However, adjustments while utilizing an inherently cleaner-burning fuel such as B20 has not been addressed [2,3]. Deployments and high demand for the Dash 86 equipment meant the engine was not available for the project.

A prime candidate for evaluation was the General Motors/AM General 6.2L/6.5L naturally aspirated engine found in the HMMWV. This engine is a four-cycle, indirect-injected, swirl-chamber diesel engine of mature design and mechanical fuel injection control.

3.3 NOx Formation Modeling - Southwest Research Institute used a computer model called ALAMO_ENGINE (A_E) to predict fuel property effects on diesel engine emissions. The A_E code is a simulation code that includes detailed gas composition data to accurately include the effects of Exhaust Gas Recirculation (EGR), residual gases, fuel composition, water from humidity in intake air, water in fuel-water emulsions, and water injected in-manifold or in-cylinder. The model also includes a complete chemical equilibrium code to compute chemical species in the combustion gases and kinetics for the formation of nitric oxide. Extensive comparisons have been made with experimental data [4-6]. ALAMO_ENGINE has extensive engine and fuels databases that included data for the GM 6.5L engine, and data for certification and biodiesel fuels.

Calculations were performed for several speeds and loads for each engine, corresponding to the cycle that the engine tests were performed, for the base and B20 fuels. The A_E code was used to determine the best strategy and operating conditions for reducing NOx prior to fuel and engine evaluations.

3.4 Fuels/Engines Evaluations – The 6.5L engine was installed in an instrumented steady-state test cell, in which smoke number, PM, CO, HC, and NOx emissions could be measured along with engine performance parameters. The engine tests were performed utilizing conditioned air at EPA-specified intake conditions: 100-kPa pressure, 25°C dry-bulb temperature, and 15°C dew point temperature.

The test protocol recommended was the ISO 8178 non-road test protocol. The non-road protocol for the HMMWV engine included up to eleven loads at two test speeds. The ISO 8178 is an international standard designed for a number of non-road engine applications. It is used for emission certification and/or type approval in many countries worldwide, including the USA, European Union, and Japan. The cycle can be defined by reference to the ISO 8178 standard. It can also be defined by specifying a test cycle equivalent to ISO 8178 such as the U.S. EPA regulation in Code of Federal Regulations, Title 40, Part 89, Subpart E, titled "Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines: Exhaust Emission Test Procedures”.

The ISO 8178 is actually a collection of many steady-state test cycles (type C1, C2, D1, etc.) designed for different classes of engines and equipment. Each of these cycles represents a sequence of several steady-state modes with different weighting factors.

The particular engine modes and their weighting factors for B-type (11 mode) test cycles are listed in Table 1. The intermediate speed is defined as the speed at peak torque, unless the speed at peak torque is less than 60-percent or greater than 75-percent of the rated speed. When the peak torque speed is less than 60-percent of the rated speed, the intermediate speed is run at the speed that represents 60-percent of the rated speed.

Table 1. Weighting Factors of B-Type ISO 8178 Test Cycles

Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque, %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Off-road vehicles											
Type C1	0.15	0.15	0.15	-	0.10	0.10	0.10	0.10	-	-	0.15

Due to variations in ignition characteristics of different fuels, the injection timing effects on exhaust emissions with the B20 fuel and engines was determined. The timing effects were initially evaluated at stock EGR levels. These data would determine any additional benefit from the B20 fuel that may be realized by a timing adjustment. The timing adjustment would be used to validate the level of timing retard identified by the modeling effort. Timing would be retarded to the limit that the PM emissions and smoke with B20 fuels equal the base fuel values. It was anticipated that timing retard would result in a fuel economy penalty.

The diluent effect of EGR has significant impacts on NOx emissions. These effects are twofold: 1) EGR reduces the oxygen content, extending combustion later into the expansion stroke, and 2) EGR levels change charge compressibility (temperature at injections), resulting in longer ignition delays and effectively retarding timing. Both effects contribute to increased PM emissions. Likewise, if EGR is un-cooled, the increase to intake temperature can offset some of the NOx reduction benefits. To maintain deployability, the evaluations were performed with un-cooled EGR to reduce the complexity of the modifications. Furthermore, cooled EGR usually results in increased heat rejection requirements for the cooling system. The typical military vehicle does not have the under hood space available to retrofit an increased cooling system volume. The EGR effects on exhaust emissions with the test fuels and engine were determined. The EGR effect was evaluated at stock timing. The EGR effect was evaluated at the level identified by the modeling effort. EGR was then increased to the limit that smoke levels with B20 fuels equal the base fuel values. It was anticipated EGR addition, like timing retard, would also result in a fuel economy penalty.

Data from the timing and EGR schedules, along with the NOx formation modeling, were evaluated to determine the best strategy for combining EGR and timing retard. The lowest cost solution, in terms of NOx reduction versus fuel economy penalty, was selected and validated with multiple emission measurements with the B20 fuel. An evaluation of the modified engines was performed using JP-8 to determine the effect of the suggested engine modifications on deployment.

4.0 EXPERIMENTAL / RESULTS

4.1 **Fuels** - A supply of EPA 49-state low sulfur, certification diesel fuel was obtained from ChevronPhillips Chemical Company. A source of B100 that has contracts with the Defense Energy Supply Center was sought. Fuel was purchased from a source in Houston, TX that supplies biodiesel to Tinker AFB. A "yellow grease" B100 fuel was added to the fuels matrix due to the unavailability of a Dash 86 engine. There have been studies that suggest "yellow grease" biodiesel has lower NOx emissions than methyl soyate biodiesel. The "yellow grease" biodiesel came from Griffin Industries. The JP-8 fuel came from AGE Refining.

4.2 **Engine(s)** - A 6.5L turbocharged engine was supplied to TFLRF. The arrangements of the intake manifolds (Figures 1 and 2), due to the packaging of the turbocharger, lead to challenges of distributing EGR reliably between the cylinder banks if a high pressure EGR loop was utilized. The benefit of a high-pressure EGR loop is that the turbocharger does not get contaminated; however, the EGR does not get mixed well, and the plumbing is difficult. A low–pressure EGR loop can mix EGR very well, but leads to soot contamination of the compressor and that can lead to compressor imbalance and failure. Currently, proposed low-pressure EGR schemes for turbocharged engines draw the exhaust after a diesel particulate filter, which was a level of complexity beyond the scope of this program. The distribution of turbocharged HMMWV engines in the military is less than 10-percent. The Army recently completed a program with a naturally aspirated 6.5L engine that was made available to the USAF program.

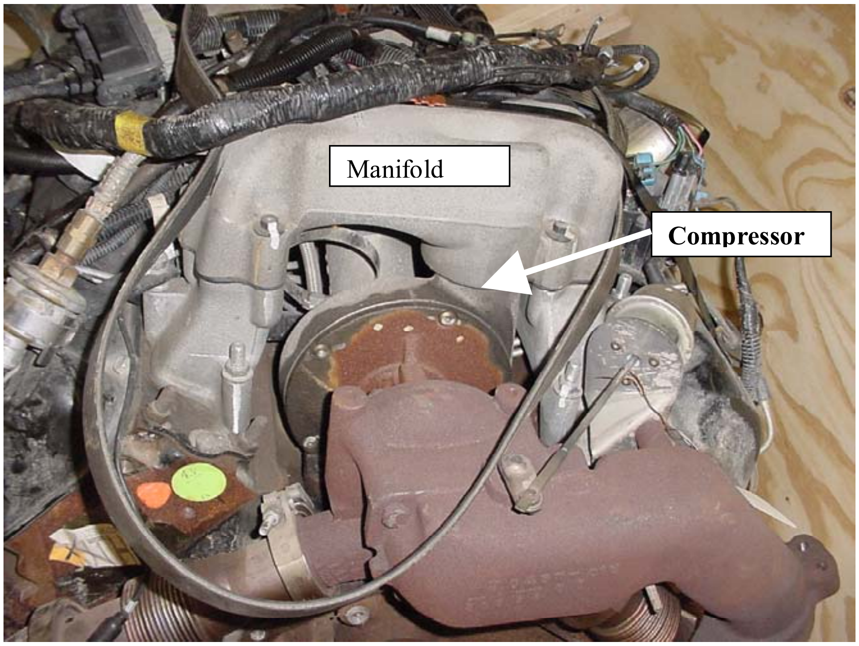

Figure 1. 6.5 Liter Turbocharged engine (Intake Manifold Arrangement)

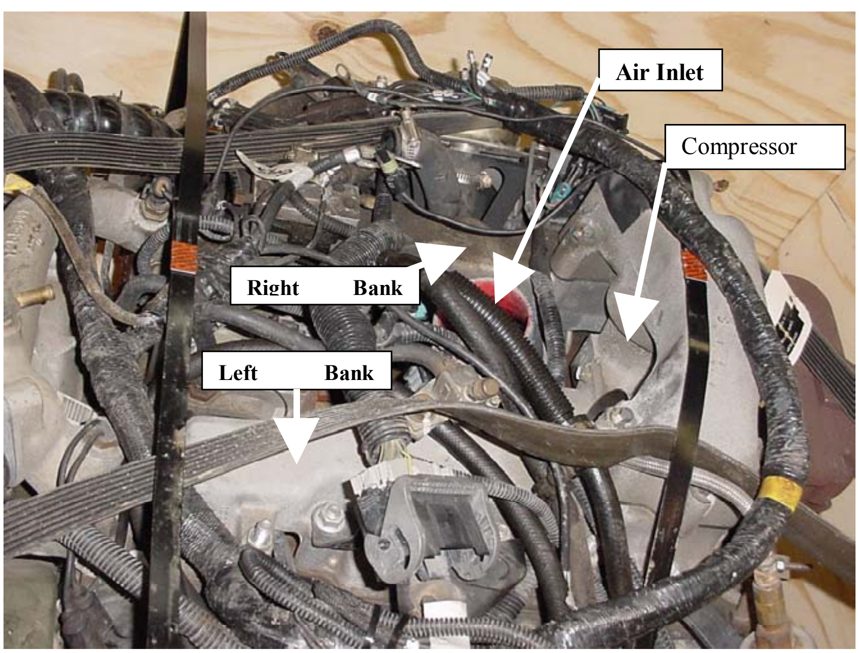

Figure 2. 6.5 Liter Turbocharged Engine (Intake Manifold Arrangement)

All 6.2/6.5L engines have an EGR passage cast into each cylinder head between the two center cylinder intake ports. On the heavy-duty versions of the engine, which the military uses, the intake manifold blocks the EGR ports. A light-duty engine intake manifold is available with cast in EGR runners that lead to an EGR valve in the intake plenum. A light-duty engine intake manifold was obtained and installed on the engine along with an EGR valve for the biodiesel work. An EGR control system was specified which utilized the engine installed vacuum system and a vacuum bleed valve. The EGR was measured by the ratio of intake manifold CO2 to exhaust manifold CO2. The EGR system was verified to function properly. A mechanism for altering fuel injection timing, via a lever and threaded rod, was mounted to the fuel injection pump. The fuel injection timing was altered manually during the course of testing. A diesel-timing meter was used to verify injection timing. The base specified injection timing at 1300-rpm, idle throttle was 4-degrees BTDC. The diesel-timing meter was originally configured for low-speed and low power settings. Efforts were extended to obtain stable timing measurements at high speed and high power settings. Test results indicated consistent timing readings at all ISO 8178 power settings.

The engine exhaust back pressure and inlet restriction was set and the initial baseline emission tests were performed in triplicate with the EPA certification diesel and B20 biodiesel fuels. The baseline and B20 fuels emissions results were used to validate the NOX modeling efforts. A Heated Flame Ionization Detector was used to determine the Unburned Hydrocarbons emissions. Non-Dispersive Infrared Analyzers were used to determine the Carbon Dioxide and Carbon Monoxide emissions. The Oxides of Nitrogen emissions were measured with a Chemiluminescent Analyzer. Smoke number was determined with an AVL-415 smoke meter, which monitors reflectance from a filter paper for a fixed volume of sample, and Particulate Matter emissions were determined gravimetrically from a mini-dilution tunnel.

The deviations from certification diesel fuel for the B20 blend is shown in Table 2. The NOx and Smoke emission values were similar to values reported in the literature. The HC emissions are contrary to results published by EPA [1] for biodiesel over a range of engines. The HC results were highly influenced by the low load operating conditions in the indirect injection 6.5L engine.

Table 2. IS0 8178 Weighted Average				
B20 Emission Deviations from DF-2 Certification Fuel 6.5L HMMWV Engine				
UHC	CO	NOx	CO2	Smoke
g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	units
26.0%	-4.9%	1.3%	0.3%	-19.8%

Modeling efforts for predicting operating conditions for lowering engine out NOx emissions with biodiesel in the 6.2/6.5L engine family was performed using the ALAMO_ENGINE model. The model variables were adjusted to compare to NOx results from the current baseline certification fuel and biodiesel fuel baseline emissions data. The eight weighted modes of the 11-mode ISO 8178 operating conditions were modeled. Initial modeling results suggested EGR would reduce brake specific NOx with the least impact on fuel consumption. However, the modeling actually suggested the current OEM timings were retarded, and would have a big impact on fuel economy if retarded further. Further timing retard and the addition of EGR would also likely result in excessive smoke and PM emissions [8]. The modeling suggested NOx may be reduced and fuel economy improved by advancing injection timing and adding more EGR.

Unfortunately the NOx model did not estimate smoke or PM impacts due to timing and EGR. The modeling results and subsequent smoke impacts were verified with engine testing. A matrix of operating conditions suggested by modeling was run with B20 in order to assess the actual NOx/smoke (PM) tradeoff. The smoke number from an AVL-415 smoke meter was used in lieu of measuring particulate because the engine sweeps could be performed more efficiently. The matrix is shown in Table 3. The dark spaces in Table 3 were not evaluated.

Table 3. Matrix for Timing and EGR Changes				
		EGR Target (%)		
		0.0	2.5	5.0
Timing Advance (CA)	**-0.5**	retard		Retard & EGR
	0.0	base		Retard & EGR
	0.5		Advance & EGR	Advance & EGR
	1.0			Advance & EGR

A matrix of operating conditions suggested by modeling was run with B20 in order to assess the actual NOx/smoke (PM) tradeoff. The deviations from certification diesel fuel for the B20 blend is shown in Table 4 for ISO 8178, 8-mode, weighted emissions for the timing and EGR variations. Also included in Table 4 are the deviations of the timing and EGR variations with respect to the base B20 results. Clocking the fuel injection pump made the timing changes, and the EGR was set by regulating the vacuum to the control valve and validated by measuring intake manifold CO2. Most data was obtained in triplicate runs. The UHC, CO, NOx, and Smoke emission values were similar to values reported in the literature for B20 with respect to DF-2. The engine responded to timing and EGR as anticipated, except for the timing retard. Timing retard had little or no increased NOx response. Slight advance with EGR reduced NOx, but increased Smoke greater than hoped, based on the weighted emission values. However, looking at the individual modes of the ISO 8178 matrix, 60% of the smoke increase was primarily due to the two full rack modes at each speed, Mode 1 and Mode 6. It was anticipated EGR should be dialed back at full-rack in order to minimize smoke impact. A 0.5-degree advance with 2.5% EGR appeared to show the best compromise of emissions, with an overall 5% Brake Specific Fuel Consumption (BSFC) penalty with respect to DF-2 fuel.

The weighted emissions were calculated using the weighting factors shown in Table 1 for each of the eight weighted modes. The NOx and other emissions (with the exception of smoke, which was not calculated on a power basis,) were calculated as shown in Equation 1.

$$wt.BSNOx = \frac{\left(\sum W_i \bullet NOx_i\right)}{\left(\sum W_i \bullet P_i\right)}$$

Equation 1

Where: wt.BSNOx = weighted 8-mode Brake Specific NOx emission (g/kW-hr)
W_i = Weighting Factor for Mode *i*
NOx_i = NOx emission for Mode *i* (g/hr)
P_i = Brake Power for Mode *i* (kW)

Thus the emissions impacts of differing operating conditions could be entered into the calculation to see which components or modes effected the final calculated result. Initial "estimated" calculations were made using no EGR and the base injection timing emissions data for the high loads, Mode 1 and Mode 6, in the weighted calculations with the data from the 0.5° timing advance and 2.5% EGR runs. The "estimated" weighted results showed a 15% reduction in smoke and a 4.3% reduction of NOx for the weighted results with respect to DF-2 when using B20. The "estimated" weighted results with respect to B20 at base timing and EGR were an 8% smoke increase and a 4.9% NOx decrease. The engine was operated to obtain data at 0.5-degrees advanced injection timing and 1% EGR for the high-load modes.

Table 4. B20 Emission Variations from Timing and EGR Changes

		UHC [g/kWh]			CO [g/kWh]			CO2 [g/kWh]			NOx [g/kWh]			Smoke [AVL]			BSFC [g/kWh]		
		EGR Target [%]			EGR Target [%]			EGR Target [%]			EGR Target [%]			EGR Target [%]			EGR Target [%]		
		0	2.5	5	0	2.5	5	0	2.5	5	0	2.5	5	0	2.5	5	0	2.5	5
B20 Emission Deviation due to timing and EGR from DF-2 Base Timing (0) and Base EGR (0%)																			
Timing Advance [°CA]	-0.5	-33%		-52%	-2%		80%	2%		5%	4%		-20%	-25%		69%	5%		7%
	0.0	-2%		-40%	-4%		79%	1%		5%	1%		-19%	-22%		70%	3%		8%
	+0.5		-44%	-52%		8%	72%		3%	4%		-7%	-18%		14%	74%		5%	7%
	+1.0			-50%			76%			4%			-15%			83%			7%
B20 Emission Deviation due to Timing and EGR from B20 Base Timing (0) and Base EGR (0%)																			
Timing Advance [°CA]	-0.5	-32%		-51%	2%		87%	2%		4%	3%		-20%	-4%		116%	2%		4%
	0.0	0%		-38%	0%		86%	0%		4%	0%		-19%	0%		117%	0%		4%
	+0.5		-43%	-51%		12%	79%		2%	3%		-7%	-19%		46%	122%		2%	3%
	+1.0			-49%			82%			3%			-15%			133%			4%

Preliminary results suggested that using 1-percent EGR at 0.5-degrees injection advance at full rack, then using 2.5-percent EGR at 0.5-degrees injection advance at low loads would result in a 4% reduction in NOx along with a 10% reduction in smoke with respect to DF-2. This approach was utilized because once the fuel injection pump was set mechanically, injection timing could not be easily varied as a function of rack setting. However, it was envisioned that a simple EGR controller could be assembled to vent vacuum to lower EGR at full-rack settings.

The "yellow grease" biodiesel was blended at 20-percent in the reference diesel fuel. The YGB20 blend was evaluated at base timing and zero EGR over the eight modes that are weighted of the ISO 8178 procedure. The YG20 blend was also evaluated at a composite of 0.5-degrees timing advance at 2.5-percent EGR for the six intermediate and light loads and 0.5-degrees timing advance at 1.0-percent EGR for the two full-rack points.

Likewise JP-8 was evaluated at a composite of 0.5-degrees timing advance at. 2.5-percent EGR for the six intermediate and light loads and 0.5-degrees timing advance at 1.0-percent EGR for the two full-rack points. Additional data from a previous program was also available for the 6.5L engine operating on JP-8.

5.0 DISCUSSION

After the operating conditions were selected for further analysis, PM emissions were measured gravimetrically for the B20, YGB20, and JP-8 fuels. The weighted brake specific PM emissions for the three fuels were measured using the "Composite" control approach of 0.5-degrees timing advance at. 2.5-percent EGR for the six intermediate and light loads and 0.5-degrees timing advance at 1.0-percent EGR for the two full-rack points. PM data for the certification DF-2 and JP-8 at baseline injection timing and EGR were taken from previous Army work with this 6.5L engine. (7)

Table 5 shows the weighted specific gaseous emission results for the fuels at the conditions evaluated. Table 6 shows the weighted Smoke, PM emission and specific fuel consumption results for the fuels at the conditions evaluated. The results shown for 0.5 degrees injection timing advance and 1-percent EGR in Table 5 and Table 6 are actually the weighted results calculated for the defined "Composite" operating condition. Included in the table with the emissions result is an estimate of the standard deviation of the weighted result. The standard deviations were estimated from the variability in multiple readings for the emissions and power, and combining uncertainties to estimate the propagation of error. The values for DF-2 and JP-8 PM emissions, and the baseline JP-8 data represent the means from earlier testing. Due to constraints, all PM emission for the test fuels at the composite conditions were single data points.

Figures 3 through 9 show the weighted brake specific mass emissions for hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen along with the weighted smoke number, Particulate Matter emissions, and brake specific fuel consumption. A one standard deviation estimate of error is included with the data bars. From Figure 3 it is evident the weighted BSHC emissions for either B20 fuels are less than the DF-2 or JP-8 emissions at any of the operating modes, including the composite condition.

In Figure 4 it can be shown that the weighted BSCO emissions for either biodiesel are equivalent to DF-2, and less than JP-8 at the baseline operating conditions, and at EGR levels below five-percent. The composite operating condition with B20 and YGB20 appear statistically similar to the baseline operating condition and DF-2 for carbon monoxide.

Shown in Figure 5 are the weighted BSCO2 emissions. Both biodiesel fuels are equivalent to DF-2, and less than JP-8 at the baseline operating conditions, and at EGR levels below five-percent. The composite operating condition with B20 and YGB20 appear statistically similar to the baseline operating condition and DF-2 for carbon dioxide. Carbon dioxide emissions are a measure of fuel consumption, thus there appears to be little fuel consumption impact due to the composite operating condition.

Shown in Figure 6 are the results for the weighted BSNOx emissions. Both biodiesel fuels show NOx values lower than DF-2 with the addition of EGR at any level. Of interest is the

NOx emissions for both of the biodiesels are greater than JP-8 at both the baseline and composite operating conditions. Both the composite and baseline operating conditions for B20 and YGB20 appear statistically similar to each other for oxides of nitrogen emissions.

In Figure 7 it can be shown that the Smoke Number emissions for either biodiesel are less than or equivalent to DF-2 at the baseline operating conditions, and at EGR levels below 2.5-percent. The composite operating condition with B20 and YGB20 appear statistically similar to DF-2 for Smoke Number due to the reduction of EGR to one-percent at the two full-rack mode points. The results suggest the composite of advanced timing and operating condition dependent mild EGR can reduce B20 NOx without a smoke impact.

In Figure 8 it can be shown that the brake specific PM emissions for the composite operating conditions for either biodiesel fuel are slightly greater than the base DF-2 result. The baseline DF-2 and JP-8 results are the means from earlier work with the same engine. The composite operating condition data for the biodiesel fuels and JP-8 represent a single measurement.

Shown in Figure 9 are the results for the weighted Brake Specific Fuel Consumption (BSFC). Both biodiesel fuels show BSFC values higher than DF-2 with the addition of EGR at any level or at any timing change. These results were not unanticipated, as B20 biodiesel fuel use has previously shown a fuel economy impact [1]. The BSFC for both of the biodiesels does not appear to change significantly due to the addition of EGR or timing change. The B20 and YGB20 appear similar for BSFC at the composite operating condition. The JP-8 appeared to show a slight improvement of BSFC at the composite operating condition.

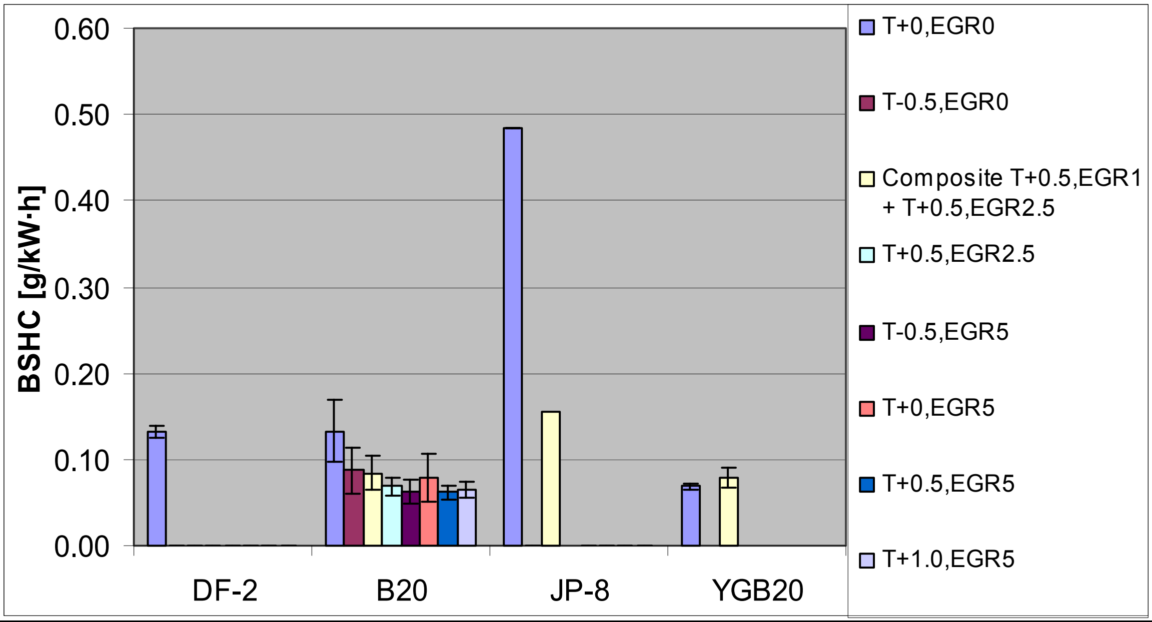

Figure 3. Weighted BSHC Emissions between Fuels and Conditions

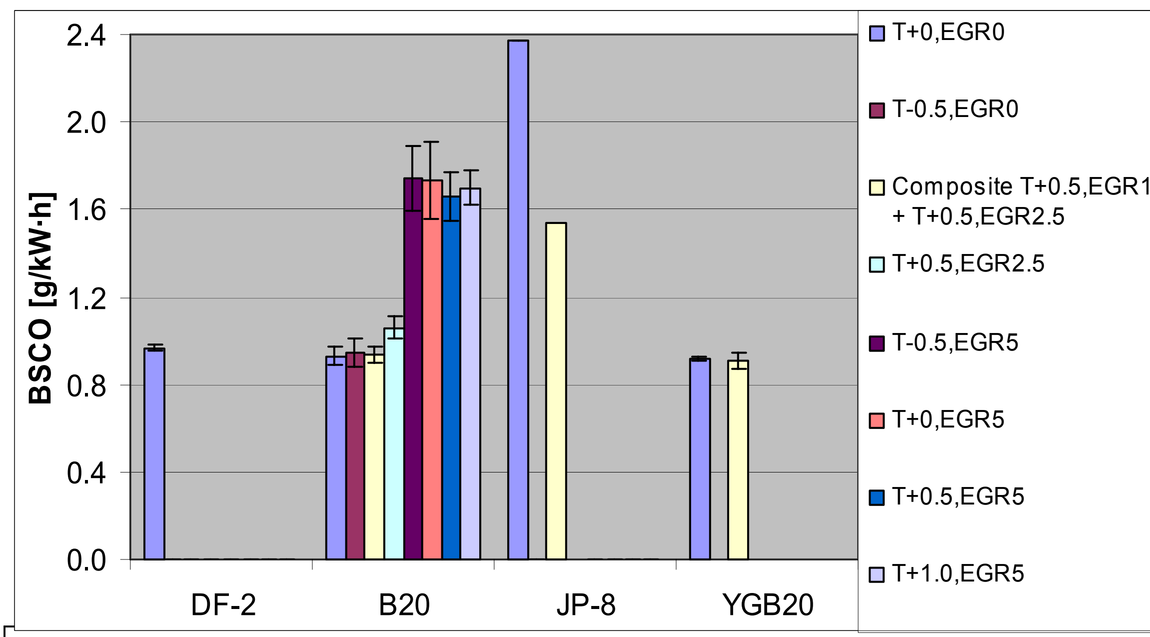

Figure 4. Weighted BSCO Emissions between Fuels and Conditions

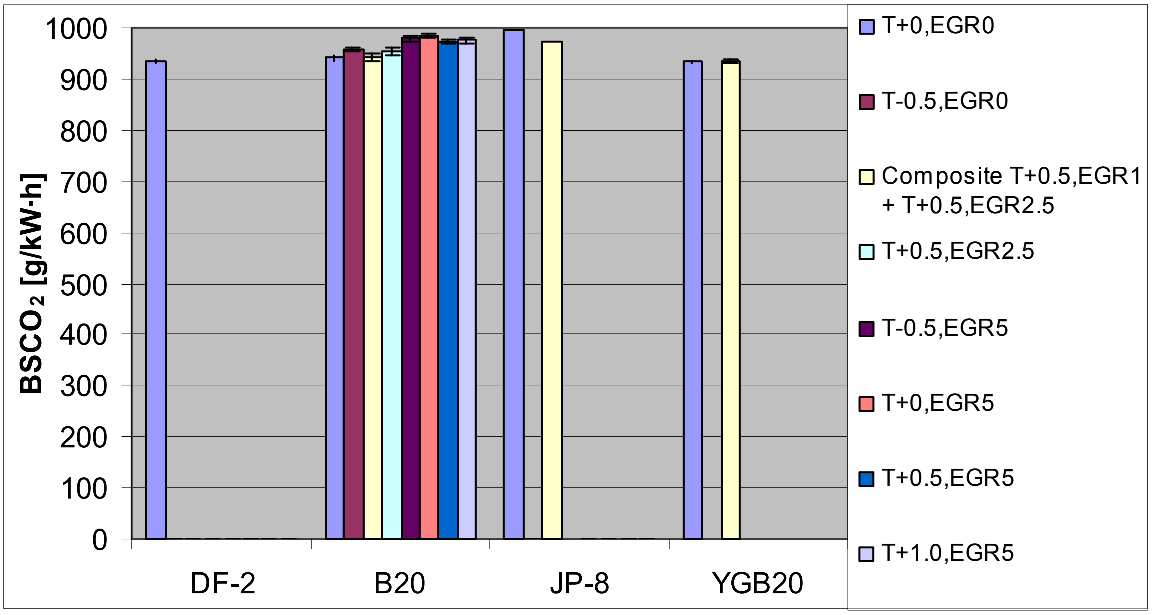

Figure 5. Weighted BSCO$_2$ Emissions between Fuels and Conditions

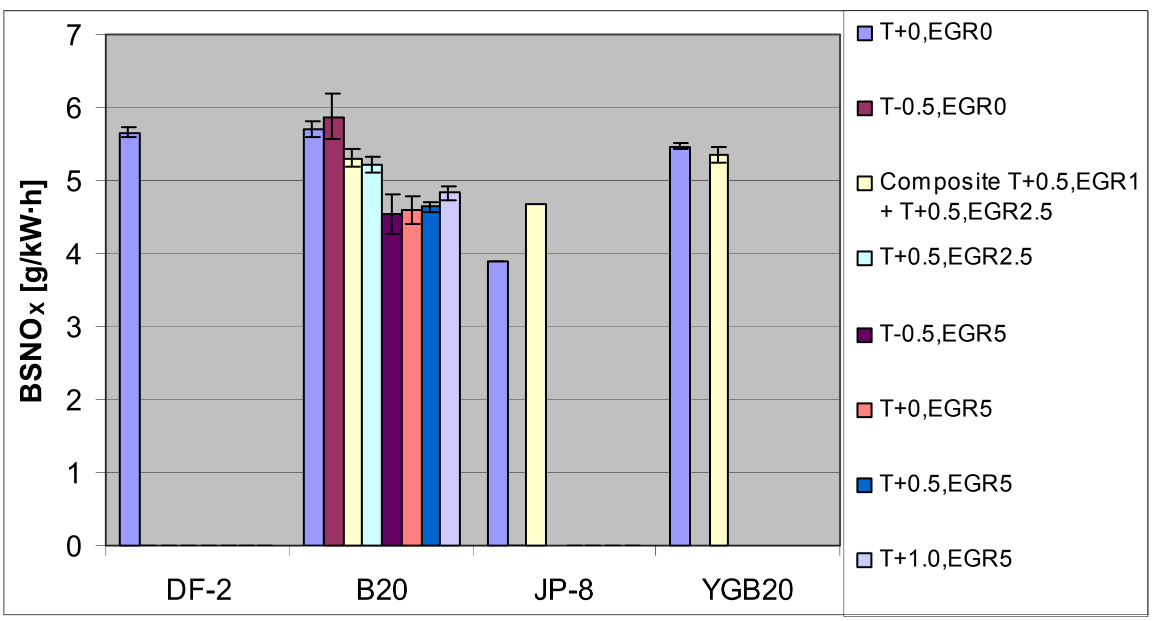

Figure 6. Weighted BSNOx Emissions between Fuels and Conditions

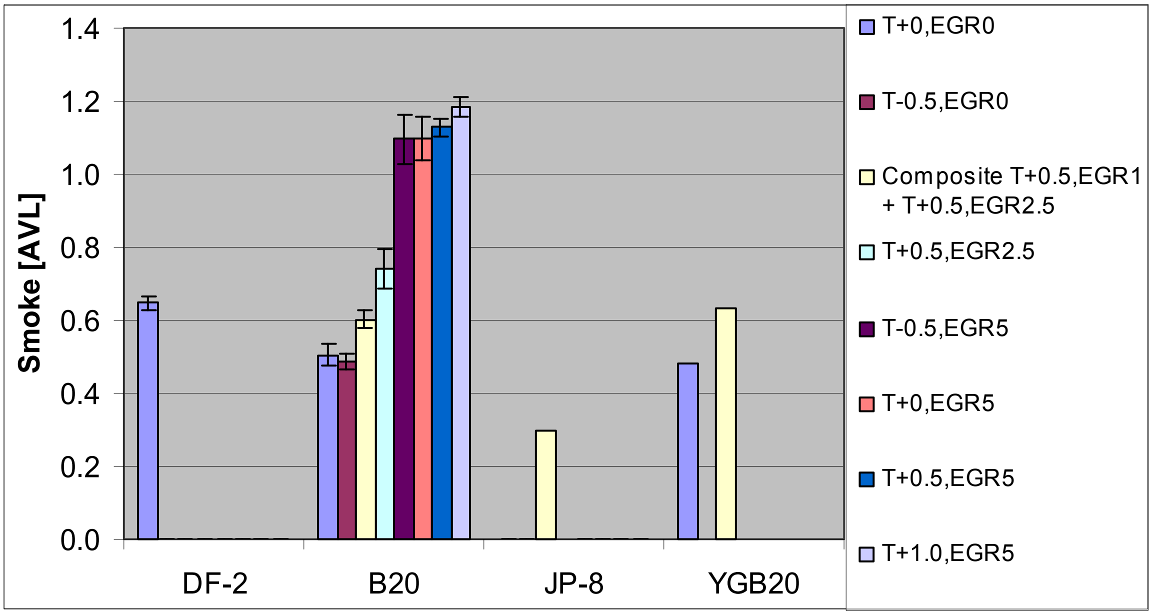

Figure 7. Weighted Smoke Emissions between Fuels and Conditions

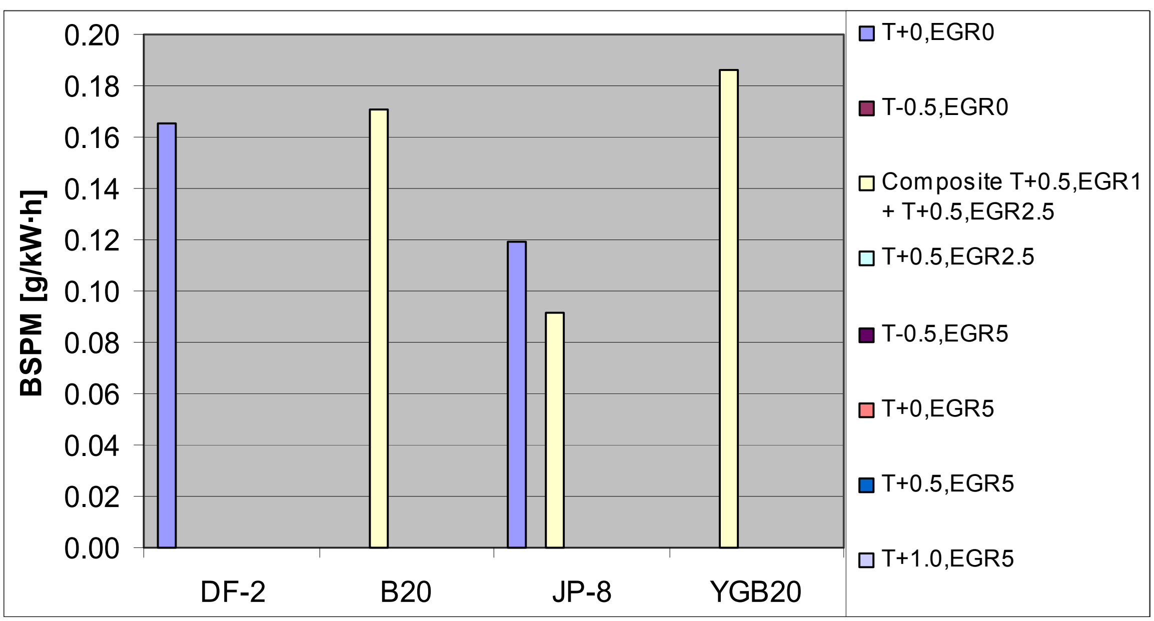

Figure 8. Weighted BSPM Emissions between Fuels and Conditions

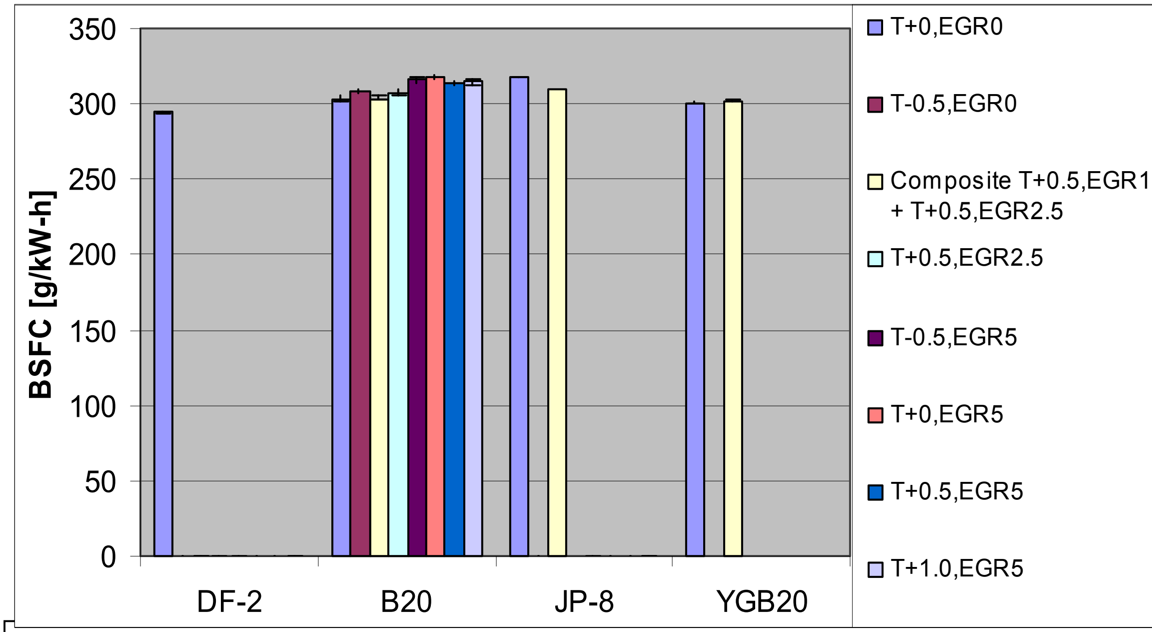

Figure 9. Weighted Specific Fuel Consumption between Fuels and Conditions

Table 5. Mode-Weighted Data by Fuel and Operating Condition

Fuel AL-27060-F — Baseline DF-2

BSHC [g/kW·hr]

0.13	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.13 ± 0.01			
+0.5				
+1.0				

BSCO [g/kW·hr]

0.97	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.97 ± 0.01			
+0.5				
+1.0				

$BSCO_2$ [g/kW·hr]

935	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	935 ± 3			
+0.5				
+1.0				

$BSNO_X$ [g/kW·hr]

5.66	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	5.66 ± 0.06			
+0.5				
+1.0				

Fuel AL-27066-F — 20% BioDiesel

BSHC [g/kW·hr]

0.13	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5	0.09 ± 0.03			0.06 ± 0.01
0.0	0.13 ± 0.04			0.08 ± 0.03
+0.5		0.08 ± 0.02	0.07 ± 0.01	0.06 ± 0.01
+1.0				0.06 ± 0.01

BSCO [g/kW·hr]

0.97	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5	0.95 ± 0.06			1.74 ± 0.15
0.0	0.93 ± 0.04			1.73 ± 0.18
+0.5		0.93 ± 0.04	1.06 ± 0.05	1.66 ± 0.11
+1.0				1.70 ± 0.08

$BSCO_2$ [g/kW·hr]

935	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5	958 ± 5			980 ± 6
0.0	942 ± 6			984 ± 5
+0.5		941 ± 7	954 ± 7	973 ± 4
+1.0				975 ± 6

$BSNO_X$ [g/kW·hr]

5.66	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5	5.87 ± 0.31			4.55 ± 0.27
0.0	5.70 ± 0.11			4.60 ± 0.18
+0.5		5.31 ± 0.13	5.22 ± 0.11	4.64 ± 0.07
+1.0				4.83 ± 0.09

Fuel AL-27081-F — JP-8

BSHC [g/kW·hr]

0.13	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.48			
+0.5		0.16		
+1.0				

BSCO [g/kW·hr]

0.97	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	2.37			
+0.5		1.54		
+1.0				

$BSCO_2$ [g/kW·hr]

935	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	995			
+0.5		974		
+1.0				

$BSNO_X$ [g/kW·hr]

5.66	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	3.88			
+0.5		4.67		
+1.0				

Fuel AL-27086-F — 20% Yellow Grease BioDiesel

BSHC [g/kW·hr]

0.13	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.07 ± 0.00			
+0.5		0.08 ± 0.01		
+1.0				

BSCO [g/kW·hr]

0.97	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.92 ± 0.01			
+0.5		0.91 ± 0.04		
+1.0				

$BSCO_2$ [g/kW·hr]

935	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	933 ± 3			
+0.5		935 ± 4		
+1.0				

$BSNO_X$ [g/kW·hr]

5.66	EGR Target [%]			
Timing Advance [°CA]	0.0	1.0	2.5	5.0
-0.5				
0.0	5.47 ± 0.04			
+0.5		5.36 ± 0.11		
+1.0				

Table 6. Mode-Weighted Data by Fuel and Operating Condition

Fuel AL-27060-F — Baseline DF-2

Smoke [AVL] (reference: 0.65)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.65 ± 0.02			
+0.5				
+1.0				

BSPM [g/kW-hr] (reference: 0.17)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.17			
+0.5				
+1.0				

BSFC [g/kW-hr] (reference: 295)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	295 ± 0.87			
+0.5				
+1.0				

Fuel AL-27066-F — 20% BioDiesel

Smoke [AVL] (reference: 0.65)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5	0.49 ± 0.02			1.09 ± 0.07
0.0	0.51 ± 0.03			1.10 ± 0.06
+0.5		0.60 ± 0.02	0.74 ± 0.05	1.13 ± 0.03
+1.0				1.18 ± 0.03

BSPM [g/kW·hr] (reference: 0.17)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0				
+0.5		0.17		
+1.0				

BSFC [g/kW-hr] (reference: 295)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5	308 ± 1.50			316 ± 1.78
0.0	303 ± 1.89			317 ± 1.51
+0.5		303 ± 2.31	308 ± 2.28	314 ± 1.20
+1.0				314 ± 1.88

Fuel AL-27081-F — JP-8

Smoke [AVL] (reference: 0.65)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0				
+0.5		0.30		
+1.0				

BSPM [g/kW·hr] (reference: 0.17)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.12			
+0.5		0.09		
+1.0				

BSFC [g/kW-hr] (reference: 295)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	317			
+0.5		310		
+1.0				

Fuel AL-27086-F — 20% Yellow Grease BioDiesel

Smoke [AVL] (reference: 0.65)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	0.48			
+0.5		0.63		
+1.0				

BSPM [g/kW·hr] (reference: 0.17)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0				
+0.5		0.19		
+1.0				

BSFC [g/kW-hr] (reference: 295)

Timing Advance [°CA] \ EGR Target [%]	0.0	1.0	2.5	5.0
-0.5				
0.0	300 ± 0.91			
+0.5		301 ± 1.24		
+1.0				

6.0 CONCLUSIONS

The following conclusions are based on the data generated in this program for the 6.5L HMMWV engine.

- Relatively minor production component changes, and selected minor operating condition changes can alter engine out NOx emissions with biodiesel fuels in a 6.5L HMMWV engine.

- A "Composite" operating condition of 0.5-degree injection timing advance, along with 2.5-percent EGR at the six medium and low loads of the ISO 8178 test cycle and 1.0-percent EGR at the full-rack loads can alter NOx emissions with Biodiesel fuels in the 6.5L HMMWV engine.

- Over the ISO 8178 test cycle weighted average NOx emissions with B20 biodiesel fuel can be similar to DF-2 emissions provided the control parameters of injection timing and EGR are adjusted based on engine load.

- For the ISO 8178 test cycle weighted average Smoke/PM emissions with B20 biodiesel fuel can be similar to DF-2 levels at the condition that gives equivalent NOx emissions. In other words, Smoke/PM emissions with biodiesel can be traded-off for improved NOx emissions.

- In this program the fuel consumption with Biodiesel fuels did not appear to be severely altered by running the engine using the "Composite" operating conditions.

- In the 6.5L HMMWV engine little difference is seen between regular biodiesel and "yellow grease" biodiesel.

- For the 6.5L HMMWV engine tested the composite control strategy did not severely impact emissions or fuel consumption when the engine operated on JP-8 fuel. JP-8 fuel appeared to result in lower weighted NOx and Smoke/PM emissions than either DF-2 or B20 at either operating condition.

7.0 RECOMMENDATIONS

Based on the results of this project the following recommendations can be made:

- Determine the validity of "Composite" control approach for lower biodiesel NOx emissions across a wider range of speeds and loads.

- Explore development of a micro-controller that monitors rack setting and engine speed to vary EGR using the vacuum system and a pulse-width-modulated vacuum controller.

- Integrate the EGR control system with the available EGR intake manifold and EGR valve for operation of the 6.5L HMMWV across the fuel engine operating range.

- Explore the effects of the "Composite" operating conditions for transient engine emission tests.

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